A Multi-functional SPM for Measurement of Micro-structured Surfaces

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論文内容要約

This thesis presents a multi-functional (MF) SPM for measurement of micro-structured surfaces. The tapping long stroke (LS) AFM mode and the non-contact scanning electrostatic force microscope (SEFM) mode of the MF-SPM are developed for the surface profile measurement of the micro-structured surfaces. The contact potential difference (CPD) measurement mode of the MF-SPM is developed for the measurement of the CPD and distinguishing of material distributions on the micro-structured surfaces.

In Chapter 1, the background, challenges and the motivations of this research are presented. Miniaturized components with micro-structured surfaces with amplitude and pitch of 100 nm to 100 μm, such as micro-optics, MEMS devices, are key elements in modern precision industries. Take the micro-optics as an example, the optical performance of the micro-optics is greatly influenced by the uniformity of the periodical micro-structures on the sample surface. Thus, the precision quantitative metrology of the sample surface is indispensable for the quality controlling of fabrication before and after each compensation manufacturing process. On the other hand, MEMS devices consists complex micro-structures that made with different materials and placed crosswise and level by level, the dielectric, purity or the contamination/defects of the micro-structures on the MEMS devices surface is also necessary to be measured to improve the performance of the MEMS devices. As a result, precision measurements of the sample profile and the surface electrical property of the micro-structured surfaces are demanded.

Conventionally, mechanical/micro stylus profiling method, optical metrology, and the scanning probe microscopy have been employed for surface profile measurement. The mechanical stylus profiler has long been used for surface profile measurement. The stage-of-the-art micro stylus profiling method has the advantages of wide measurement range with nano-scale resolution in vertical direction. However, the measurement accuracy is greatly influenced by the stylus tip radius and the contact force is so large to damage the micro-structured surfaces. On the other hand, the optical metrology, which has the advantage of non-contact/non-destructive detection and fast full aperture scanning with large area as well as high accuracy, is another main approach for surface profile measurement of micro-structured surfaces. The disadvantage of the optical metrology is that its lateral resolution is restrained to the half wavelength of the light and it is also difficult for optical metrology to measure the micro-structured surfaces with steep local slopes. Comparing with the contact micro-stylus profiler and optical profile evaluation method, the SPM method, for example, the AFM

and STM, has the advantages of atomic level resolution and nano-scale accuracy. AFMs are the most commonly employed for the surface profile of micro-structured surface. Newly developed AFMs have extended the scanning range from μm to mm, some high speed AFMs with new scanning strategy have also been developed. The AFMs have three scan modes, the contact mode, tapping mode and non-contact mode. The contact mode has the advantage of highest lateral resolution but also has the disadvantage of contact force between the probe tip and the sample surface which would damages the sample surface and blunts the probe tip. On the other hand, the tapping mode can remove the lateral contact force and maintain the high measurement resolution. In order to realize the nondestructive measurement, the non-contact mode is always applied. However, the measurement resolution will be reduced compared with the contact mode and the tapping mode. Another problem of the non-contact mode is that the short tip-to-sample distance during scanning, which makes the scanning instable and vulnerability to mechanical vibrations. Furthermore, the scanning speed is also limited for avoiding tip-to-sample collision. These short-comings make it difficult for the conventional SPMs to measure the surface profile with steep local slopes and large amplitudes. It is necessary to develop a new kind of SPM for the high accuracy profile measurement of micro-structures with a large tip-to-sample distance as well as the ability of profile measurement of large amplitude and high aspect ratio micro-structures with steep local slopes.

On the other hand, among the surface property measurement, it is important to characterize the electrical properties of different materials for the MEMS devices. Surface potential and contact potential difference (CPD) are usually imaged or measured. The EFM and KPFM have been employed for surface potential imaging and CPD measurement. However, in most situations the surface potential imaging and CPD measurement should be carried out in the vacuum environment and the conventional EFM and KPFM can only measure the surface potential and CPD value but not the surface profile. It is novel if a new kind of measurement instrument which can measure the surface profile and CPD value simultaneously in normal atmosphere is developed.

To realize the surface profile measurement and CPD measurement of micro-structured surfaces, the motivations of this research are:

- Development of a prototype of a multi-functional scanning probe microscope (MF-SPM) which can realize the surface profile and surface electrical property measurement simultaneously.
- The MF-SPM has the high lateral resolution tapping LS-AFM mode which can realize surface profile measurement of micro-structured surface with large amplitude and high aspect ratio.
- The MF-SPM has the non-contact SEFM mode which can realize non-damage, safer, faster surface profile measurement of complex micro-structured surfaces with high quality coating or soft materials.
- The MF-SPM has the CPD measurement mode which can distinguish the material distributions on the sample surface by the measurement of contact potential differences.

In Chapter 2, the prototype of a multi-functional scanning probe microscope (MF-SPM) and its tapping LS-AFM mode is described. Since it is difficult for alignment of the light-lever construction of conventional AFMs, a self-vibration/detection oscillation unit which consists of a tuning fork quartz crystal resonator (TF-QCR) and two electrochemically etched probe tips is employed for the tip-to-sample interaction detections. The self-manufactured probe tip has a very low cost. It also has a apex radius of about 50~100 nm and a half angle which is smaller than 10º as well as a high aspect ratio which is larger than 10:1, this provides the ability of surface profile measurement of micro-structured surfaces with large amplitudes and steep local slopes. The probe tip is vibrated vertically to the sample surface at the resonance frequency of the oscillation unit. When the probe tip is tapping the sample surface, the frequency shift signal will be generated and detected by a phase-locked loop circuit. The frequency shift signal is fed into a PI controller to adjust the probe tip in Z direction so that the value of the frequency shift value during the scanning can be kept as constant. As a result, the probe tip trace during the constant frequency shift scanning can be considered as the measured surface profile. An ultra-precision Z scanner which has a long stroke more than 50 μm and a high precision positioning is employed to drive the probe to move in Z direction so that the quantitative surface profile measurement of large amplitude sample surface can be promised. The approaching and retracting curves are detected by using the prototype MF-SPM and its high resolution tapping LS-AFM mode to demonstrate its basic feasibility in surface profile measurement. Surface profile measurement of a grating sample with a small amplitude of about 100 nm and a prism sheet sample with a large amplitude of 25 μm and a pitch of 50 μm are carried out. Finally, one sectional profile of a Fresnel lens which has the step microstructure with an almost 90º steep sidewall is well measured by the MF-SPM of its tapping LS-AFM mode. In comparison with the measurement result of a commercial optical sensor, the resolution and accuracy advantages of the tapping LS-AFM mode of the MF-SPM are demonstrated.

In Chapter 3, the noncontact scanning electrostatic force microscope (SEFM) mode of the MF-SPM is presented. By adding two switches for turning on the bias voltage and converting the input signals of the PI controller, the MF-SPM can alternate from tapping LS-AFM mode to the SEFM mode. Comparing with the conventional noncontact AFM, the tip-to-sample distance of the SEFM mode of the MF-SPM can be expanded to larger than 100 nm, which would provide safer, faster scanning and the ability of measurement of micro-structured surfaces with steep local slopes. However, the electrostatic force is influenced by the tip-to-sample distance and the electrical properties of the sample surface simultaneously. A dual height method is proposed to eliminate the influence of the electrical properties on the electrostatic force so that the accurate tip-to-sample distance can be obtained. Surface profile measurement of a grating with step structures is measured by the SEFM mode of the MF-SPM. The measured amplitude and pitch show a good accordance with theoretical values. However, some measurement errors exit at the rising edge and the falling edge of the measured step profile. A new unidirectional feed-forward controlled scan method is then proposed to replace the old bidirectional feedback controlled scan method for improving the measurement accuracy and scanning speed. The comparison experiment results demonstrate the effectiveness of the new scan method in scanning accuracy and speed improvement. The drift of the SEFM mode of the MF-SPM is also analyzed. Two kinds of drift resources, the mechanical drift and the resonance frequency drift, which are the main measurement uncertainty sources, are analyzed. According to the simulation result, the smaller the signal sampling time interval between the upper trace and the lower trace at the same position on the sample surface, the smaller the measurement error caused by the drift. As a result, a vertical reciprocating scan method is proposed to reduce the influence of the drift when the dual height method is applied. Comparison experiment results demonstrate the effectiveness of the vertical reciprocating scan method in drift reduction and measurement accuracy improvement.

In Chapter 4, optimization of the SEFM mode of the MF-SPM is described. When a small amplitude micro-structured surface is measured, the relationship between the electrostatic force and tip-to-sample distance can be simplified and expressed by the sphere-plane model, which has been utilized in Chapter 3. However, the relationship between the electrostatic force and tip-to-sample distance varies at different position when a large amplitude (>10μm) micro-structured surface is measured. A numerical finite difference method (FDM) is utilized to accurately explore the relationship between the electrostatic force and tip-to-sample distance with considering the shape of the probe tip and the topography of the sample surface. The good accordance between the experiment result and the simulation result by the FDM proves the feasibility of the FDM. A new scan method, which is named as the multi-$\Delta f(z)$ curves method, which optimizes the relationship between the electrostatic force and the tip-to-sample distance at different scanning position, is then proposed to explore the accurate surface profile of large-amplitude micro-structured surfaces. Comparison experiment results demonstrate the effectiveness of the multi-$\Delta f(z)$ curves method in optimization of the profile measurement of large-amplitude micro-structured surface by the non-contact SEFM mode of the MF-SPM.

In Chapter 5, the contact potential difference measurement mode of the MF-SPM is presented. The method for detecting the contact potential difference (CPD) value on the sample surface is introduced. By scanning the sample surface three times with two different bias voltages, the surface profile and the CPD value can be obtained simultaneously. Experiments of the CPD detecting are carried out to show the feasibility of the CPD mode of the MF-SPM. Although the measured absolute CPD value shows differences from the theoretical values, the different materials on the sample surface can be distinguished by the CPD measurement mode of the MF-SPM.

In Chapter 6, conclusions and achievements of this thesis are discussed.

Keywords: SPM, EFM, AFM, Microscope, Surface, Profile, Contact potential difference, Measurement, Control, Micro-structures, Micro-optics, Large amplitude, High aspect ratio, Tapping, Drift, Non-contact, Vertical reciprocating, Unidirectional, Bidirectional, Feed-forward, Feedback.